First Year's Progress Report for
NASA Applied Information Systems Research Program

Title of Project:
Integration of Orbital, Descent and Ground Imagery for Topographic Capability Analysis in Mars Landed Missions

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Since our project started in March 2006, we have been developing methods for photogrammetric modeling and processing of Mars orbital images. The following is a summary of our progress, which has fulfilled and, in some cases, exceeded the designated tasks for the first year..

1) A methodology for orbital data processing (including a semi-automatic hierarchical matching technique) is being developed and examined.
2) Bundle adjustment of orbital image exterior-orientation parameters was performed to reduce errors overall.
3) A Victoria Crater DTM (digital terrain model) was generated from HiRISE stereo images.
4) The ground image network was constructed and adjusted using bundle adjustment.
5) Comparison has been made of DTMs derived from HiRISE and MER stereo pairs.

1. Theoretical and Technical Progress

1.1 Orbital stereo image matching and tie-point selection

A hierarchical stereo matching technique has been developed based on an image pyramid with five levels consisting of: 1/16th, 1/8th, 1/4th, 1/2nd, and original level (size) of the stereo images. The matching process starts at the 1/16th level and proceeds to the original level. At the 1/16th level, interest points are automatically generated using the Förstner operator; they then are matched in the stereo images using cross correlation. Points whose maximum correlation exceeds a certain threshold (e.g., 0.8) are selected as matched points. Next, the locations of these matched points are adjusted to achieve maximum correlation in the 1/8th through the 1/2nd size levels. New interest points are also generated using the Förstner operator and matched on the subsequent level. The search window used to match these new interest points is determined based on the parallax surface of the Delaunay triangles formed by the previously matched tie points. At the original-image level, tie points are manually selected for areas of the crater wall where interest points are often unobtainable because the pixel brightness values are too homogeneous. These manually selected points are then refined by cross correlation-based matching. In the final step, a grid with a spacing of 75 pixels is defined and corresponding points of the grid points are found by a matching process.

A stereo pair of HiRISE images that cover Vitoria Crater (TRA_000873_1780 acquired on 2006-10-03 and PSP_001414_1780 acquired on 2006-11-14) was processed to test the developed stereo matching method. Up to the 1/2nd level, 5180 points were obtained. These points were concentrated at the crater rim and the crater bottom. For the crater wall, 322 points were selected manually. Finally, 2064 new points were selected from the original-size stereo images, resulting in a total of 7566 points. All of these points were used to generate the HiRISE DTM.

1.2 Geometric modeling of Mars orbital imagery

The push-broom imaging geometry of Mars orbital images such as MOC NA and HiRISE is mathematically modeled by a collinearity equation with changing exterior orientation (EO) parameters along the scan lines. Since the orbital image was acquired within a short period of time, we can assume that the EO parameters change only linearly, along the image scan lines. The positions and pointing angles of the HiRISE sensor can be parameterized with first-order polynomial (i.e., linear) models. In the bundle adjustment (BA), the initial values for the polynomial coefficients were estimated by fitting the original exterior orientation data retrieved from the SPICE kernels. Solving for these polynomial coefficients, instead of the actual EO parameters of each scan line, ensures that results of this bundle adjustment processing are more stable and accurate.

For the stereo pair of HiRISE images, 287 automatically matched interest points were selected based on the aforementioned hierarchical stereo matching method. Sixty-six of them became image tie points for the bundle adjustment, while the remaining 221 points became check points. After BA, the back-projection residuals for the check points were reduced, on average, from 2.0 to 0.7 pixels. After BA, the 3D coordinates of the 7566 matched points in object space were obtained by photogrammetric triangulation. Subsequently, Kriging interpolation was performed to generate a DTM and an orthophoto of Victoria Crater.

In order to further improve the absolute accuracy of orbital images, ,we have already started developing a combined bundle adjustment method in which MOLA data is incorporated as absolute ground control for the orbital images. MOLA ranges and MOLA 3D ground point coordinates are being treated as measurements with small standard deviation. A preliminary test has been performed using a pair of MOC NA stereo images and MOLA data at MER's Gusev Crater landing site. Inconsistencies between the MOC NA stereo pair and the MOLA data have been reduced significantly, from about 100 pixels to less than 5 pixels.

1.3 Bundle adjustment of the ground image network

A ground image network is constructed by using tie points to link the panoramas and images taken along the rover traverse. We have developed a systematic method to automatically select tie points from panoramic images taken at one position. This tie-point selection method consists of five steps: interest-point extraction using Förstner operator, interest point matching, parallax verification, graph consistency verification, and, finally, tie-point selection by gridding.

Cross-site tie points are even more difficult to find due to often significant differences between different panoramas in image resolution, looking angle, and illumination conditions. Recently, we developed an innovative method for automatic cross-site tie-point selection based on modeling and matching of rocks from adjacent rover sites. In this method, rocks are extracted from dense 3D ground points generated by stereo matching and then modeled using such analytical surfaces as hemispheroids, semi-ellipsoids, cones and tetrahedrons. Modeled rocks are then matched from two rover sites by a combination of rock model matching and rock-distribution-pattern matching. The resulting matched rocks are used as cross-site tie points for the bundle adjustment.

Bundle adjustment of this image network provides accurate image orientation parameters and ground positions of tie points. During MER mission operations, bundle adjustment of the image network has usually improved 2D accuracy from tens of pixels to a sub-pixel to 1 pixel level. It has improved 3D accuracy from a meter to a centimeter level within a local area. Consequently, high-precision rover localization and topographic mapping can be achieved.

We performed bundle adjustment of a local image network along the rim of Victoria Crater from Sol 943 to Sol 1061. The position of Sol 955 was fixed. When comparing the telemetry-provided positions with the bundle adjusted rover positions, errors were found to range from 0.94% to 7.69%. The relative error reached 7.69% at the position of Sol 992-994 (3.59m accumulated difference over a distance of 46.72m traveled from Sol 955 to Sol 992). The maximal accumulated difference is 19.72m on Sol 1060 (4.72% of distance of 417.99m traveled since Sol 955). After bundle adjustment, the measurements of ground features from rover images taken at different rover positions was more consistent. Also, these measurements were more consistent with those measured from HiRISE stereo images.

1.4 Orbital versus ground comparison

To validate the HiRISE DTM, we compared it to the BA-based MER localization data and to a local DTM derived from ground imagery. Six landmarks were measured from the bundle-adjusted rover images and overlaid on the HiRISE DTM. The coordinates of these landmarks from both orbital and ground localization results were compared and shifted so that the sum of the residuals was zero. Standard deviations of the residuals in X, Y and Z were found to be 1.28m, 1.35m, and 1.48m, respectively.

The HiRISE DTM of Duck Bay was then compared to the DTM generated from the bundle-adjusted Pancam images of that area to further validate the HiRISE DTM. Differences in the horizontal position of six common features were measured to evaluate the horizontal difference between the two DTMs. Standard deviations of the residuals in X and Y were 0.43m and 0.75m, respectively. Vertical differences are depicted by the differences in elevation between the two DTMs. The standard deviation of this elevation difference was 1.25m.

2. Future Tasks

Future tasks of this research include:

- Development of efficient recognition and matching procedures for finding corresponding objects in both orbital and ground images,
- A combined bundle adjustment of orbital and ground data, and
- Integrated mapping of major craters and hollows at the MER landing sites using orbital and ground images.

3. Publications and Presentations

Li, R., K. Di, J. Hwangbo, and Y. Chen 2007. Integration of Orbital and Ground Images for Enhanced Topographic Mapping in Mars Landed Missions. Paper and presentation at Annual NASA Science Technology Conference, College Park, MD, June 19-21.

Di, K., and R. Li 2007. Topographic Mapping Capability Analysis of Mars Exploration Rover 2003 Mission Imagery. Paper and presentation at 5th International Symposium on Mobile Mapping Technology (MMT 2007), Padua, Italy, May 28-31.

Li, R., K. Di, A. Howard, L. Matthies, J. Wang, and S. Agarwal 2007. An Integrated Approach to Autonomous Long-Range Mars Rover localization. Journal of Field Robotics, Vol. 24, No. 3, pp.187-203.

Di, K., S. Agarwal, J. Wang, R. Li, A. Howard, and L. Matthies 2007. New Methods for Automated Mars Rover Localization. Presentation at the ASPRS 2007 Annual Conference, Tampa, FL, May 7-11.

Li, R., K. Di, J. Wang, X. Niu, S. Agarwal, E. Brodyagina, E. Oberg, and J.W. Hwangbo 2007. A WebGIS for Spatial Data Processing, Analysis, and Distribution for the MER 2003 Mission. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 6, pp. 671-680.

Li, R., R.E. Arvidson, K. Di, M. Golombek, J. Guinn, A. Johnson, M. Maimone, L.H. Matthies, M. Malin, T. Parker, S.W. Squyres, and W.A. Watters 2007. Opportunity Rover Localization and Topographic Mapping at the Landing site of Meridiani Planum, Mars. Journal of Geophysical Research-Planets, Vol. 112, No. E2, E02S90, doi:10.1029/2006JE002776.

Li, R., K. Di, and J. Hwangbo 2006. Integration of Orbital, Descent and Ground Imagery for Topographic Capability Analysis in Mars Landed Missions. Presentation at Mars Applied Information Systems Research Program Investigators’ Workshop, College Park, MD, October 3-5.

4. Personnel

PI Dr. Ron Li (2 summer months per year) worked on the overall methodology and evaluation of orbital data processing results. Co-I Dr. Kaichang Di (50%) coordinated the research and worked on geometric modeling of the integration of orbital, descent and ground imagery. A Ph.D. student, JuWon Hwangbo, and a master’s student, Yunhang Chen, participated in this effort, helping to develop orbital data processing methods and software.